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APPLICATION OF A RATIONAL-PROBABILITY ANALYSIS FOR DETERMINATION OF ULTIMATE DESIGN LOADS ON LARGE, FLEXIBLE, MILITARY AIRCRAFT

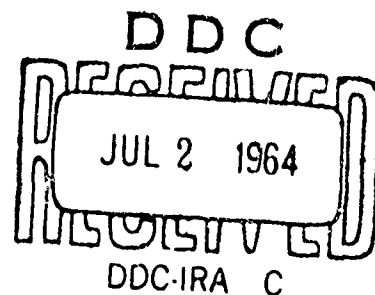*WILLIAM H. AUSTIN, JR.*

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FOREWORD

This in-house report was prepared by personnel of the Structures Branch, Airframe Division, Directorate of Strategic and Tactical Systems Engineering, under system 101 A the B-52 weapon system. Work conducted from October 1963 to March 1964 is reported.
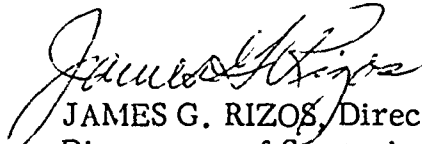
Data utilized in this report were collected and reduced by the University of Dayton Research Institute under subcontract to the Boeing Company. Further data analyses were conducted by Messrs. Robert P. Gerami, George B. Herider, and William J. Hippenmeyer and by Captain Albert A. LoSchiavo of the Structures Branch.

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ABSTRACT

Recent experiences with B-52 aircraft have indicated that the current structural design criteria are inadequate for large, flexible, military aircraft. A rational-probability analytical procedure has been established to overcome this problem. This analysis determines ultimate loads for which the vehicle must be designed in order to achieve the specified acceptable failure rate due to structural overload. The basis for the analysis is the acceptable failure rate, the dynamic spectral analysis, and the spectral exceedance curves. By use of this analysis, mission and performance trade-offs can be established in terms of probability of failure due to structural overload. With some modification, it is believed that this type of analysis can, and should, be applied to all types of aircraft.

This Technical Documentary Report has been reviewed and is approved.

JAMES G. RIZOS, Director
Directorate of Strategic and Tactical
Systems Engineering

LIST OF SYMBOLS

$\overline{A}$ environmental response factor σ_y/σ_w

b   scale parameter in probability density distribution of root mean square environmental velocity

L   spectral shaping parameter, feet

$M(y)$ average number of cycles of specified response per second of flight exceeding y

$M(y_F)$ average number of cycles of specified response per second for the desired failure rate

N_0 average number of cycles of specified response per second of flight

P   proportion of total time in disturbed environment

T_F time to failure (hours)

$T(\Omega)$ amplitude of response to unit sinusoidal gusts of frequency Ω

V   true airspeed, feet per second

y   any response parameter

σ_w root mean square environmental velocity

σ_y root mean square of response

$\Phi(\Omega)$ power spectral density function

Ω reduced frequency, $\dfrac{\omega}{V}$ radians per foot

ω frequency, radians per second

SUBSCRIPTS

$_1$ normal environment

$_2$ severe environment

w   environmental

y   response

INTRODUCTION

With the advent of low-level contour operations and high-utilization rates on the B-52 fleet, a series of accidents and incidents occurred as a result of excessive loads on the empennage. After an extensive study of all data available, it became obvious that the traditional structural design philosophy outlined in current military structural specifications was inadequate to insure a satisfactory level of safety for such a large, flexible, military aircraft. For this reason, a structural design philosophy based on statistical concepts was established for application to a redesign of the B-52. This philosophy is not new, but it is believed that this was the first time that such an approach had been taken on an operational, manned aircraft. Much of the procedure has been outlined in References 1, 2 and 3, and the entire analysis is based on power spectral density techniques outlined in these references.

The rational-probability analysis is based on three specific items -- the acceptable failure rate, the dynamic spectral analysis, and the spectral exceedance curves. Certain assumptions were made for the purpose of this analysis, but these are primarily in the form of ground rules. Advances in the state-of-the-art and additional research will further enhance this technique and should make it applicable to all classes of aircraft. The procedure presented herein is applicable to large, flexible, military aircraft. Application to commercial aircraft would be possible by a change in exceedance curves. Application to fighter-type aircraft will be possible with a modification in exceedance curves and their format, and the dynamic spectral analysis.

THE POWER SPECTRAL APPROACH

During the last several years, the power spectral density approach to the analysis of airplane motions and loads in turbulence has been developed to the point where many aircraft structural engineers consider the approach the most rational method available for calculations of aircraft gust loads.

The nature of the power spectral approach and some applications are outlined in References 1, 2, and 3. These references indicate that atmospheric turbulence can be represented as a continuous random disturbance characterized by power spectral density functions and certain probability distributions. The subject of the actual shape of the power spectrum is a matter of controversy, but these shapes are all rather similar and the use of any one of these should not cause significant errors as long as a consistent procedure is used.

To date, most spectral analyses use the "NACA," or the Reference (2), power spectrum with a scale of turbulence of 1000 feet for all altitudes. For this reason, this shape is used in this report. The probability distributions of the magnitude of these power spectra (the root mean square gust velocity) must be based on large amounts of statistical data from aircraft operations. The relations derived in Reference 4 can be used to relate the acceleration experiences of operational aircraft to the probability distributions of the root mean square gust velocities. This procedure has been given a very thorough treatment in Reference 2.

THE FAILURE RATE

The most important aspect of the rational-probability analysis is the recognition and identification of an acceptable rate of structural failure. We should note that there is a certain unknown rate of failure associated with the present structural design criteria. A reasonable rate of failure can be specified as follows:

**LOSS OF ONE AIRCRAFT DUE TO STRUCTURAL OVERLOAD
SHALL BE EXPECTED IN 1000 AIRCRAFT LIFETIMES.**

This is essentially the same criteria that was applied to the B-52 in the program for structural improvement. In that case, however, only 700 aircraft were involved, so the probability of loss was less than one in the fleet's lifetime. This rate can be moved up or down, depending on what the using command will accept. The important point is that no aircraft can be designed for a zero-failure rate.

The first step in the rational-probability analysis is to determine total time to failure, T_F. This time is established as follows:

$$T_F = \text{fleet life to failure} = \text{one aircraft lifetime x 1000 aircraft (hours)} \tag{1}$$

To use a power spectral exceedance curve, we must convert time-to-failure to cyclic form as follows:

$$M(y_F) = 0.5/(T_F \times 3600) \text{ cumulative cycles per second} \tag{2}$$

THE DYNAMIC ANALYSIS

The dynamic analysis is used to establish the statistical properties of the dynamic load responses of the aircraft to random environmental excitation. These statistical properties of the response are the quantities $\overline{A}$ and N_o, which must be computed for all major load responses throughout the airframe.

The quantity denoted as $\overline{A}$ is the ratio of the root mean square value of a specified response parameter y to the root mean square value of environmental velocity:

$$\overline{A} = \frac{\sigma_y}{\sigma_w} = \frac{1}{\sigma_w} \left[\int_0^\infty \Phi_w (\Omega) \, T^2 (\Omega) \, d\Omega \right]^{1/2} . \tag{3}$$

$\overline{A}$ can be looked upon as an operator that operates on environmental velocity and yields the specified response, y. The quantity denoted by N_o is considered to be a characteristic frequency of the airplane response, y, to turbulence and is expressed

$$N_o = \frac{1}{2\pi} \left[\frac{\int_0^\infty \Phi_y (\Omega) \, \Omega^2 \, d\Omega}{\int_0^\infty \Phi_y (\Omega) \, d\Omega} \right]^{1/2} . \tag{4}$$

N_0 gives the number of times that the response, y, crosses the mean value of y with positive slope per second of flight. It may also be considered the total number of cycles of the response y per second of flight.

Both $\overline{A}$ and N_0 are dependent on characteristics of the airplane, flight condition, and power spectral shape. $\overline{A}$ is particularly sensitive to changes in airplane damping, so care must be exercised to insure that adequate stability derivatives are included in the equations of motion for the dynamic analysis.

The dynamic analysis should include all aircraft rigid body degrees of freedom and significant elastic modes.

If possible, the effects of all automatic flight control systems and possible nonlinearities at large values of environmental velocities should be considered in the analysis. To apply this analysis to the spectral exceedances curves, the investigator must use the same input spectrum and must base the statistical response parameters, $\overline{A}$ and N_0, on true environmental velocity, not "equivalent" velocity. Values of $\overline{A}$ and N_0 should be established throughout the flight regime of the aircraft for the various major components of the airframe.

THE ENVIRONMENT

The environment is expressed in the form of power spectral exceedance curves for each phase of a mission. The exceedance curves presented herein are for a maneuver plus gust environment and, as such, apply only to aircraft that will be used the same as, or similar to, the B-52. Since the shape of a power spectrum for maneuver plus gust is undefined at present, we shall assume that the power spectrum of atmospheric turbulence presented in Reference 2 represents the shape of the gust plus maneuver power spectrum. This power spectrum of atmospheric turbulence is specified by Equation (5), in which L = 1000 for all altitudes and is written

$$\Phi_w(\Omega) = \sigma_w^2 \ \frac{L}{\pi} \ \frac{1 + 3\,\Omega^2 L^2}{(1 + \Omega^2 L^2)^2} \tag{5}$$

If we can believe that an environment can be described by changes in angle of attack or sideslip, perhaps the use of a power spectrum of velocities that are orthoganol to the flight path can be justified. Much more effort is necessary in this area. The probability distribution of σ_w (root mean square equivalent environmental velocity) can be defined from operational data. We have defined this data for several thousand hours of B-52 load history (VGH) and established the values in Table 1 using the methods given in Reference 2. The spectral exceedance curves, based on Equation (6), have been derived for various phases of a mission. Equation (6) specifies that

$$\frac{M(y)}{N_0} = P_1\,e^{-\frac{y}{Ab_1}} + P_2\,e^{-\frac{y}{Ab_2}} \tag{6}$$

TABLE 1

VALUES ESTABLISHED FOR VARIOUS PHASES OF A MISSION

Mission Phase	P_1	b_1	P_2	b_2	L
Contour low-level	0.9974	3.62	0.0026	7.62	1000
Climb	0.145	2.17	0.0115	4.16	1000
Cruise	0.075	2.06	0.005	5.75	1000
Descent	0.160	2.50	0.0465	4.16	1000

With the exception of the contour low-level mission phase, mission phase, rather than the altitude, seems to cause the greatest variations in the exceedance data. This may be due in part to the fact that the B-52 analyses used true, rather than equivalent ($V\sigma^{\frac{1}{2}}$), airspeeds to determine response parameters. The values given in Table 1 should be considered preliminary values. More data are being collected daily.

DERIVATION OF ULTIMATE DESIGN LOADS

If we use the design mission profiles and usage, the spectral exceedance curves, the calculated response parameters, ($\overline{A}$ and N_0), and the acceptable failure rate, ultimate design loads are derived by the following procedure.

a. Establish gross weight-speed-altitude blocks for each phase of the mission within the mission profiles, and identify the $\overline{A}$'s and N_0's that are applicable to these blocks.

b. Use the proper spectral exceedance curves to construct load exceedance curves $M(y)$ vs y for each block within each mission phase.

c. Take a weighted average of the load exceedance curves based on time or distance within each block and mission phase. This will result in an average-load exceedance curve for the aircraft.

d. Use the $M(y_F) = .5/(T_F \times 3600)$, determined previously, to ascertain the corresponding value of y from the average exceedance curve for the aircraft.

e. The load, y, that has been determined must be added to a weighted mean load to establish the total load. This load is the ultimate design load that will satisfy the failure-rate criteria.

Obviously, steps a through e represent only one way to arrive at these loads. Further application of the method will undoubtedly uncover superior methods.

CONCLUSIONS

The rational-probability analysis represents the most logical method for determining aircraft design loads. This does not mean, however, that there are no limitations to the method. There are uncertainties involved in the technical data, and these must be resolved. Changes in usage of aircraft by the using command will cause variations in the probable failure rate, and actions to be taken as a result of such changes in usage must be defined. In spite of the limitations involved, in applying a rational-probability analysis we believe that this method can, and should, be applied to all future designs of aircraft.

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